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The Unsteady Pressure Field and Vorticity Production at the Suction Surface of a Pitching Airfoil

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Background The objective of this work is to develop techniques for the control and management of separated flows over airfoils, particularly under unsteady operating conditions. The results are expected to help achieve the ultimate goal, which is flow management for highly maneuverable aircraft.

The key requirements for successful management of unsteady separation over airfoils are: an understanding of the vorticity production and transport over the airfoil surface, the ability to identify the flow state reliably in real time, and the availability of optimal flow controllers that can be activated, when needed, to modify the flow state in the desired manner. In addition, there are issues that need to be resolved in order to achieve the successful integration of these components into an active feedback control system.

In an investigation of a generic, unsteady, separating flow, Ramiz and Acharya (1989a,b) examined the dynamics of formation of a separation zone, and showed that relatively simple techniques involving measurements of the wall static pressure may be used to obtain reliable indicators of flow state. In these experiments, an unsteady separation was introduced in a boundary layer by the motion of a separation generator (a spanwise flap) into the flow. The development of the flow was shown to be governed by a balance between two mechanisms; one responsible for the accumulation of vorticity at the flap, and the other for the detachment and downstream convection of the vorticity. Phase-

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conditioned measurements of the time-varying flow direction at various locations downstream of the flap, and corresponding wall pressure data were used to track the separation as it developed. A number of possible criteria for flow-state identification, based on the unsteady wall-pressure measurements, were investigated, and two techniques were shown to have good promise. One of these is based on a comparison of the wall pressure signature with a preset threshold, while the other involves an examination of the time derivative of the pressure signal.

Unsteady flow over two-dimensional pitching airfoils The present paper addresses the issue of flow development over a pitching symmetric airfoil. An extensive body of work has been reported in recent years, describing experiments that examine the flow over airfoils undergoing prescribed pitching motions; in most cases these were sinusoidal oscillations about a mean angle of attack. The studies were largely motivated by the need to understand helicopter blade aerodynamics and, more recently, by interest in aircraft supermaneuverability. The bulk of these investigations focused their attention on obtaining an understanding of dynamic stall and the influence of parameters such as airfoil geometry, Reynolds number, oscillation amplitudes and rates. Although knowledge of this phenomenon has improved, (McCroskey (1982), Walker et al. (1985), Reynolds and Carr (1985), Robinson (1988)), some of the underlying mechanisms are not yet understood clearly. In addition, much needs to be done in order to develop effective means to *control* the unsteady separation. Specifically, one needs a clear understanding of the unsteady production of vorticity, its accumulation and detachment from the near-wall region. The establishment of a vorticity balance and a knowledge of the time scales of the evolutionary process are needed for an understanding of the process, and will be a prerequisite for the development of suitable control techniques.

Experiments and results We are carrying out experiments to understand this process in the flow over a NACA 0012 two-dimensional, symmetric airfoil undergoing a controlled pitching motion. The airfoil has a chord of 12 inches and a thickness 12% of chord. Measurements have been made over a Reynolds number range (based on chord) between 28,000 and 120,000. In the unsteady experiments, the airfoil was pitched up from an angle of 0 degrees to 40 degrees at constant velocity; that is, with a ramp-type time motion history. It was then held at this final angle. The non-dimensional pitch rate based on chord length was varied between 0.03 and 0.77.

A flow visualization study was first carried out to map the sequence of events that occur in the region around the leading edge and the suction surface during the pitch-up motion, from the initial fully attached flow condition to the occurrence of dynamic stall. Fig. 1 shows a sample of photographs from a sequence of smoke-wire flow visualization pictures, for a Reynolds number of 28,000 and a pitch rate of 0.154, taken at different instants during the motion of the airfoil. For reference, it is useful to know that the static stall angle for these conditions is around 13 degrees. It is possible to identify a number of events in the unsteady process that culminates in the shedding of the dynamic stall vortex. During the initial stages of the pitch up, a zone of streakline distortion or reversal is seen close to the surface in the leading edge region. This zone grows along the chord, as seen in the photograph at 11 degrees, and extends all the way to the trailing edge as the airfoil motion progresses (at an angle of around 15 degrees in this instance). Simultaneously, fluid from the trailing edge region flows upstream along the surface of the airfoil, as seen in the photograph at 25 degrees. The behavior of the flow in these zones, the growth and interaction of the two zones, as well as a number of other events (which will be described in the full paper), were systematically examined over the range of parameters to produce maps such as the one shown in Fig. 2. Here, for example, Region I is bounded by two lines. The lower line is the locus of points at which the streakline reversal zone has extended over 12 % of the chord. Along the upper line, this zone has just reached the trailing edge. The upper edge of Region III is the locus of conditions at which the leading edge vortex is shed from the airfoil.

In another phase of the experiments, these events were examined for the signature that they imposed on the wall pressure distribution over the suction surface. The unsteady pressure variation was recorded at 22 locations along the surface during the pitch-up motion, for the same range of parameters. These data were then used to obtain chordwise pressure distributions over the suction surface at different instants during the motion. Fig. 3 shows a sample of these data, for three different pitch rates (0.036, 0.074 and 0.182), at an instant when the airfoil was at an angle of attack of 20 degrees; that is, halfway through its motion. The significantly different states of development of the flow in these cases is reflected in the difference in the pressure distributions. The pressure distribution at static conditions, for which the airfoil is fully stalled, is also shown for reference. The chordwise variation of pressure over the suction surface during the pitch-up motion is shown in Fig. 4 for two sets of conditions. Fig 4(a) shows the evolution of surface pressure for a pitch rate of 0.074 and a Reynolds number of 120,000; the data of Fig. 4(b) are for a pitch rate of 0.49 and a Reynolds number of 88,000. A detailed examination of data such as these yielded several interesting results. The two figures are representative of two classes of behavior, distinguished by low and high pitch rates. In each instance, a suction peak begins to form in a region near the leading edge. As the pitch-up motion continues, the magnitude of the peak increases and it moves much closer to the leading edge. At a later instant, a zone or 'plateau' of constant pressure is seen to develop at a location which is the position along the suction surface where the leading edge vortex ultimately forms and develops. Beynond this stage, the sequence of events is different for the two cases. At low pitch rates, the leading edge vortex remains bound to the surface only until such time as the pressure levels of the suction peak and the constant pressure 'plateau' are the same. It then grows in size and moves down the surface. At higher pitch rates, the vorticity is bound to the airfoil for a longer period. The constant pressure 'plateau' deforms into a suction peak that characterizes the low pressure core of the leading edge vortex. Vorticity accumulates in this region for a longer period before the vortex grows and moves over the suction surface. The imprint of these events on the pressure evolution is seen clearly in the two figures.

The motion of the surface and the flow events within the viscous region over the suction surface are strongly coupled. The unsteady separation process and the related sequence of events discussed earlier are affected by the vorticity generated at the wall. The accompanying acceleration effects and change in the convective scales result in what Ericsson (1989) refers to as the moving-wall effect. It can be shown that for both steady and unsteady flows, the flux of vorticity *from the surface* is proportional to the instantaneous free-stream pressure gradient. Figs. 5(a) and 5(b) show the variation of wall vorticity flux from the suction surface during the pitch-up motion for the conditions of Figs 4(a) and 4(b) respectively. It is seen that the vorticity flux is confined primarily to the forward portions of the suction surface, and that during the initial phase of the motion this flux is negative in a region very close to the leading edge. The progression of certain significant events such as these, seen in the evolution of both the pressure and the wall vorticiy flux, were tracked for a range of pitch rates and summarized in composite plots such as those shown in Figs. 6(a) and 6(b). A detailed description of these plots and their significance will be described in the presentation, and the correlation between this information and the sequence of events that make up the dynamic stall phenomenon will be discussed. Finally, the implications of these results on the requirements for successful control of the unsteady separation will be examined.

References

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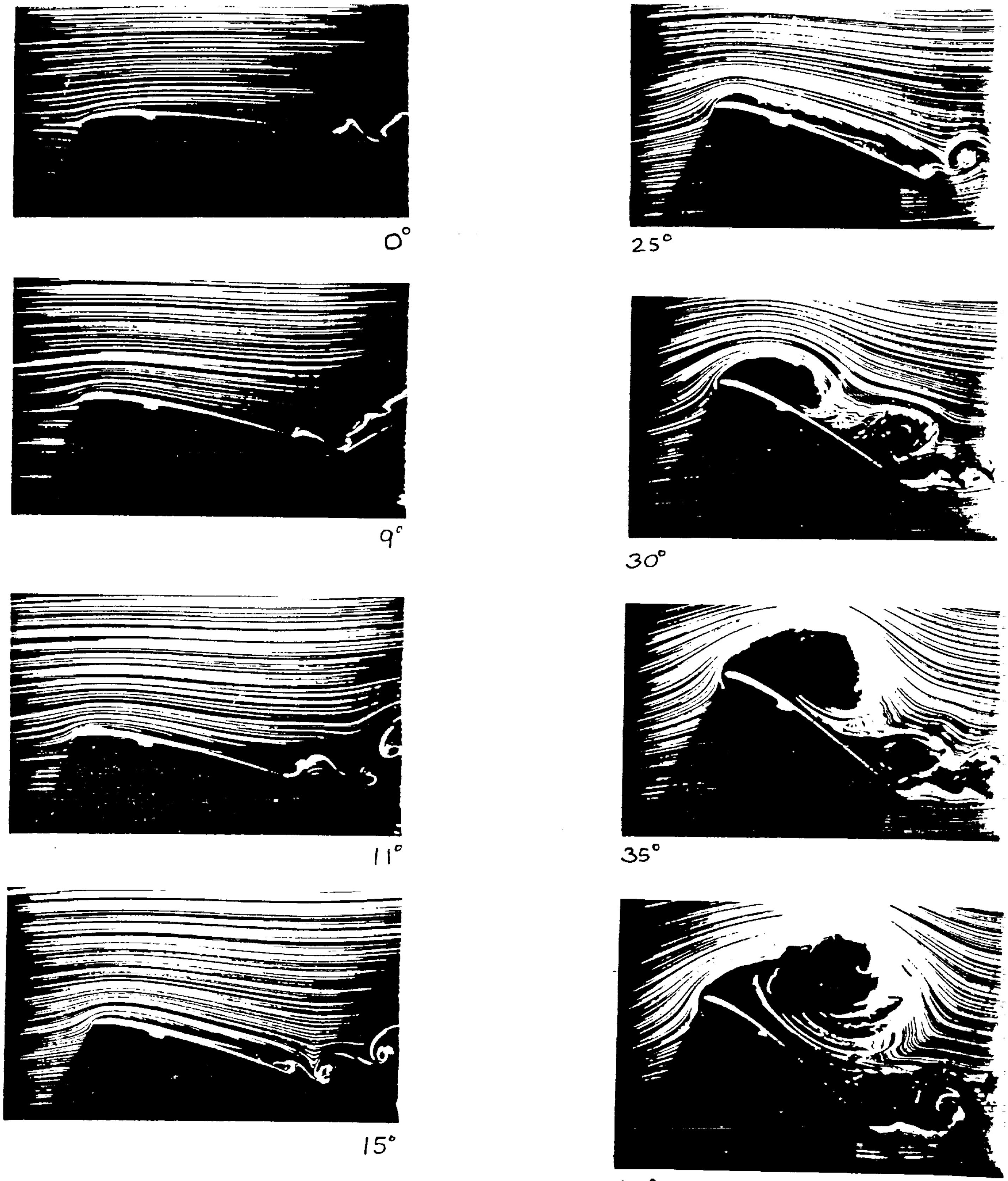


Figure 1

CHRONOLOGICAL EVENTS OF DYNAMIC SEPARATION PROCESS

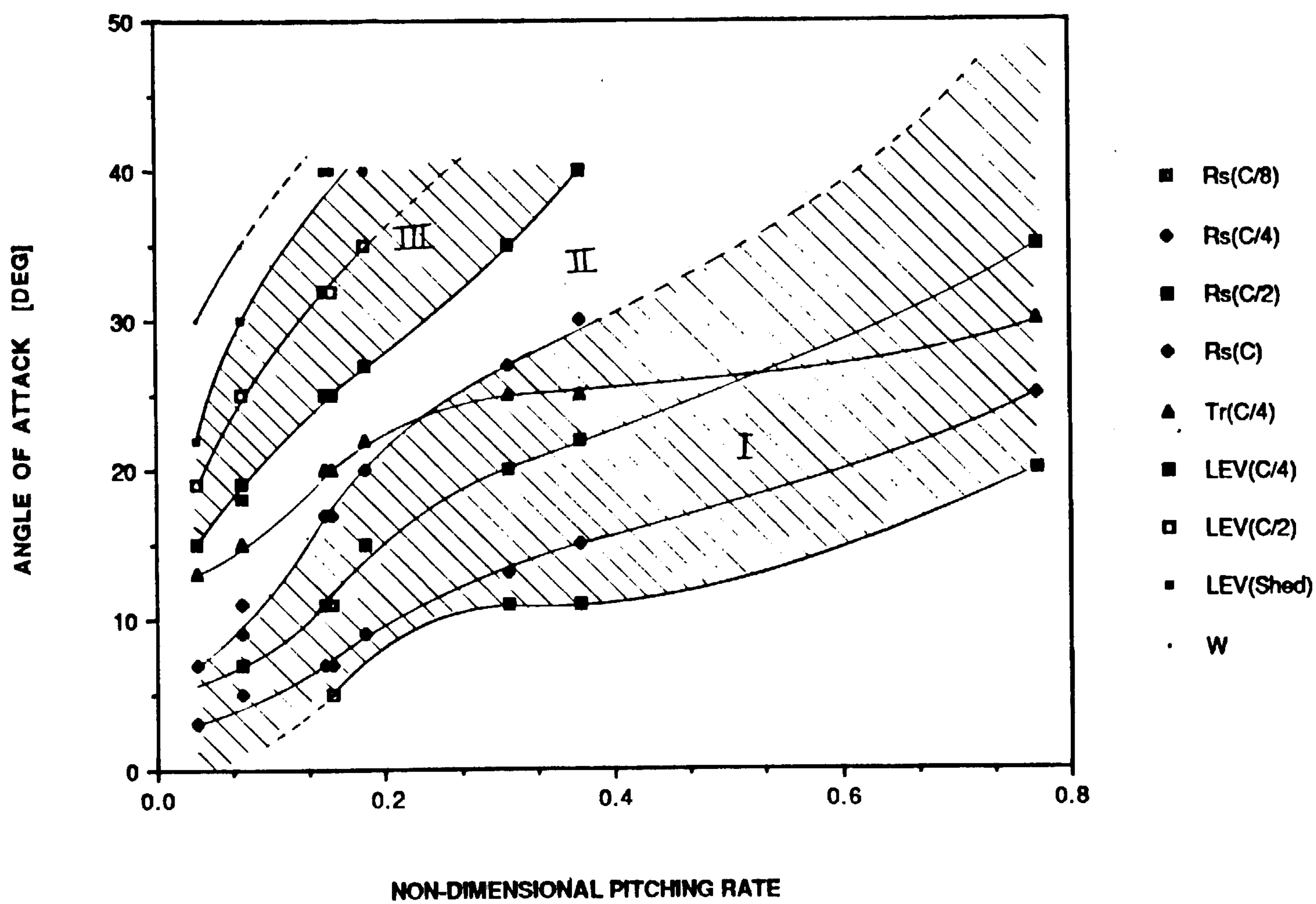
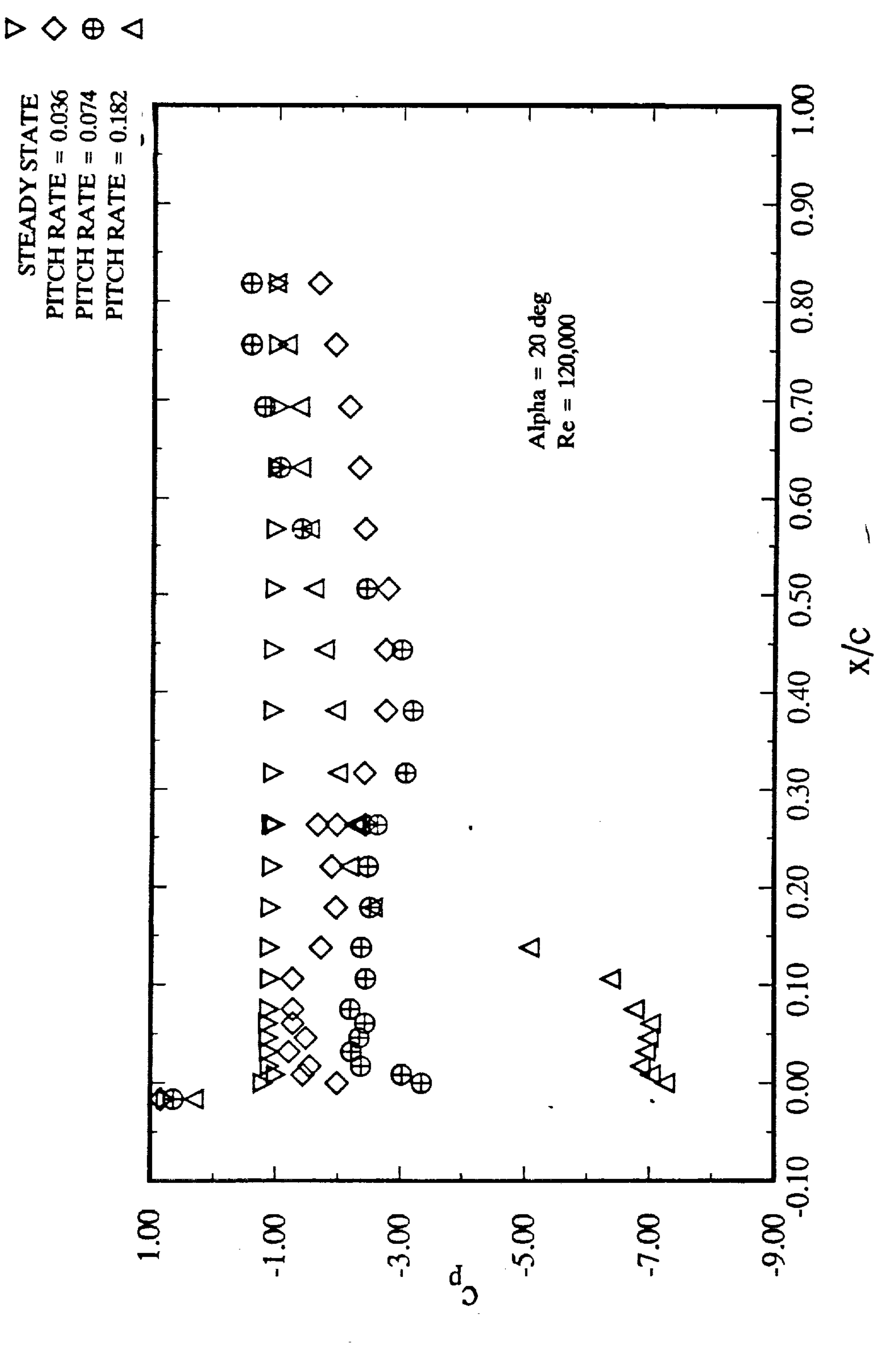


Figure 2



STEADY STATE
PITCH RATE = 0.036
PITCH RATE = 0.074
PITCH RATE = 0.182
Alpha = 20 deg
Re = 120,000
1.00
-1.00
-3.00
-5.00
-7.00
-9.00
C_p
-0.10
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
x/c

Figure 3

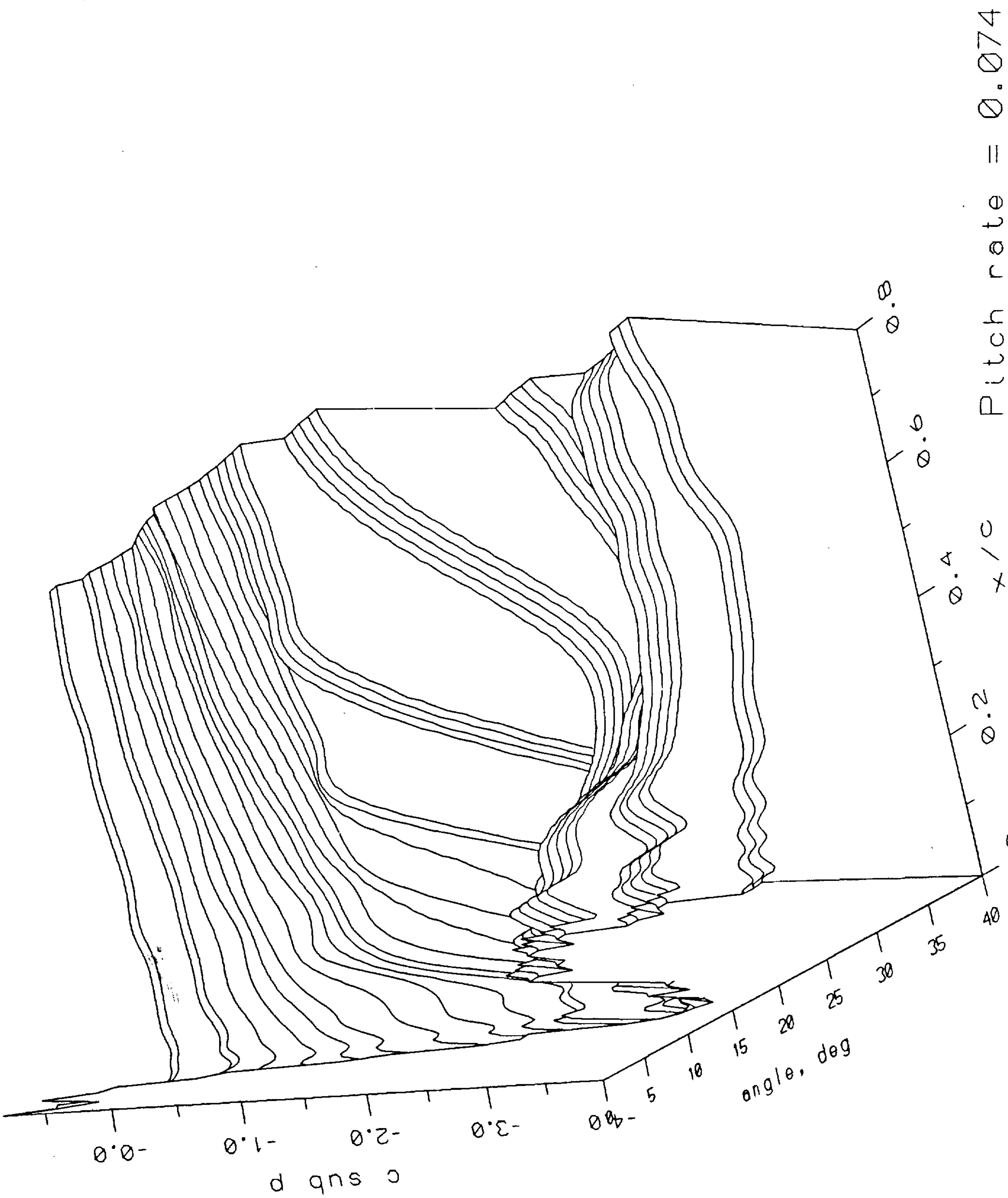
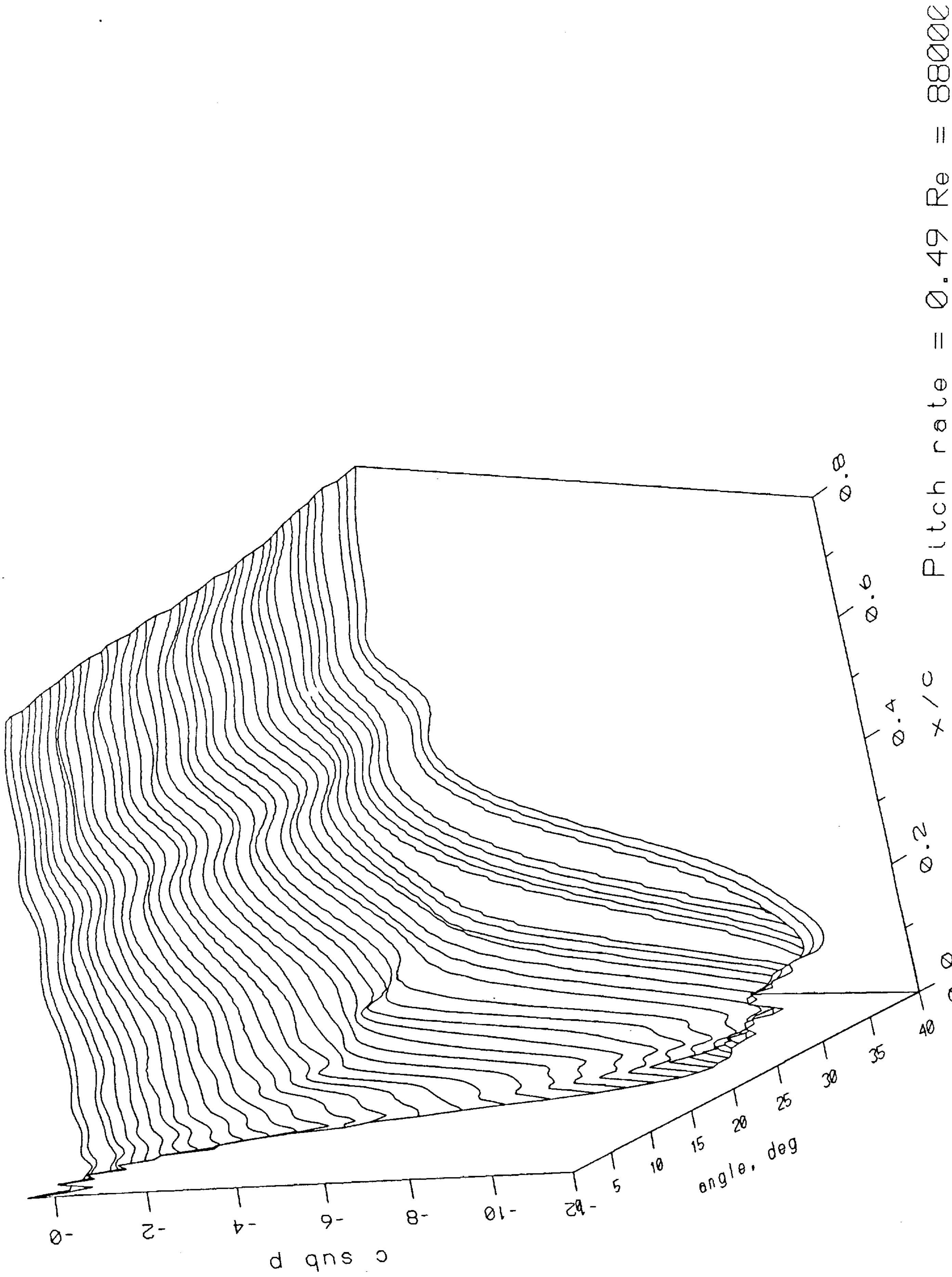

Pitch rate = 0.074
x/c
0.0
0.2
0.4
0.6
0.8
angle, deg
5
10
15
20
25
30
35
40
c sub p
-0.0
-1.0
-2.0
-3.0
-4.0

Figure 4(a)



Pitch rate = 0.49 Re = 8800
x/c
0.0
0.2
0.4
0.6
0.8
angle, deg
5
10
15
20
25
30
35
40
c sub p
-0
-2
-4
-6
-8
-10
-12

Figure 4(b)

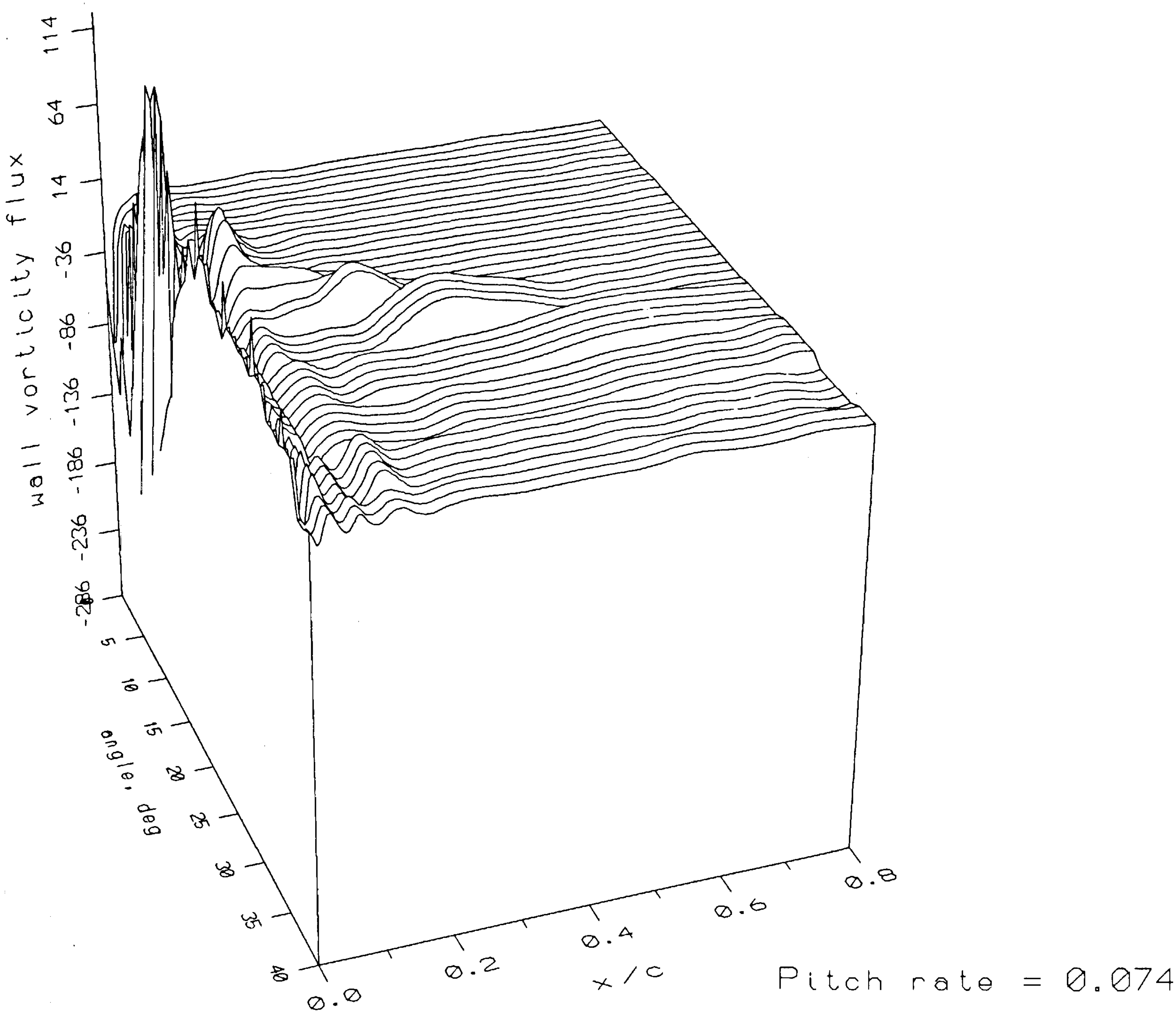
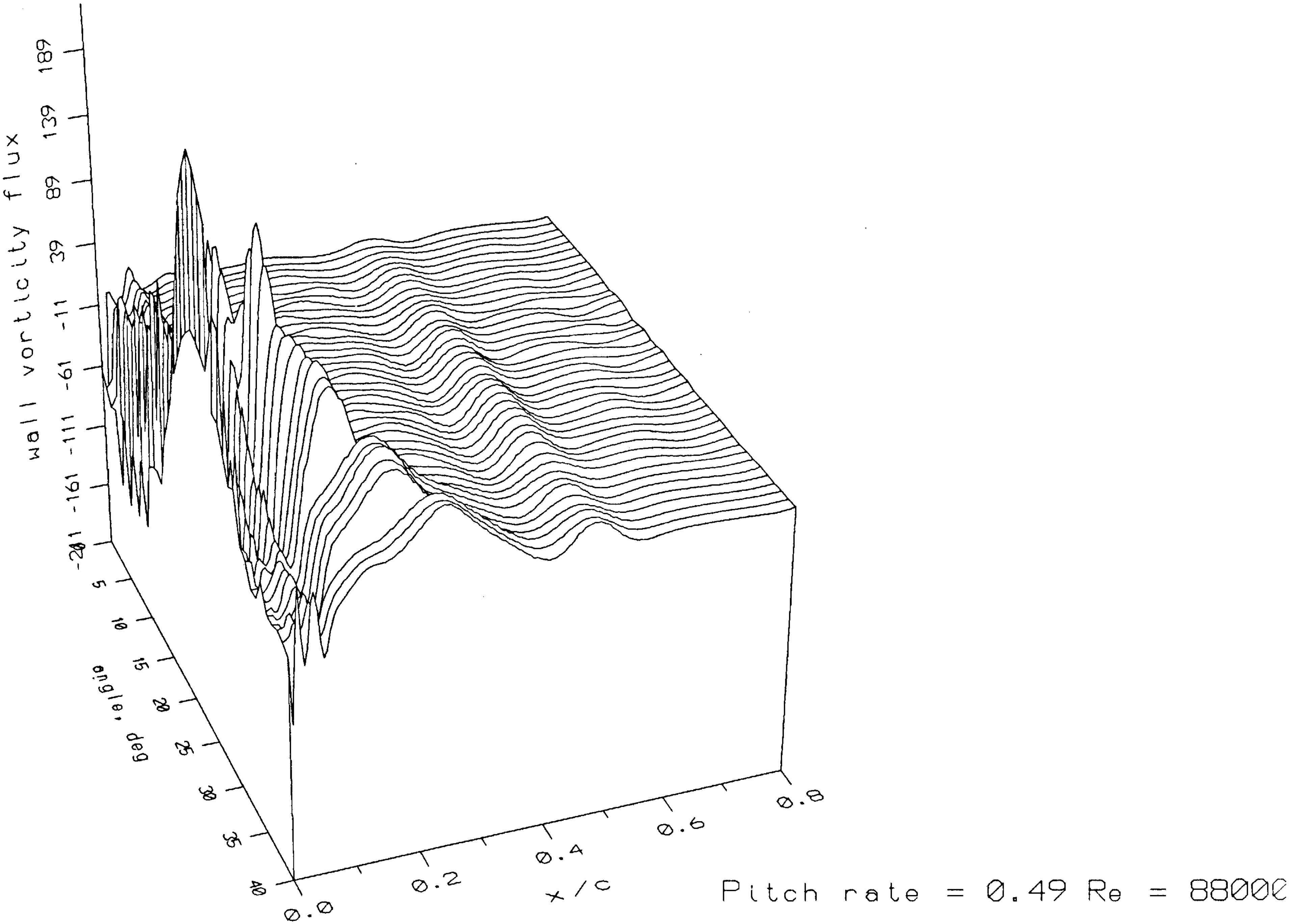
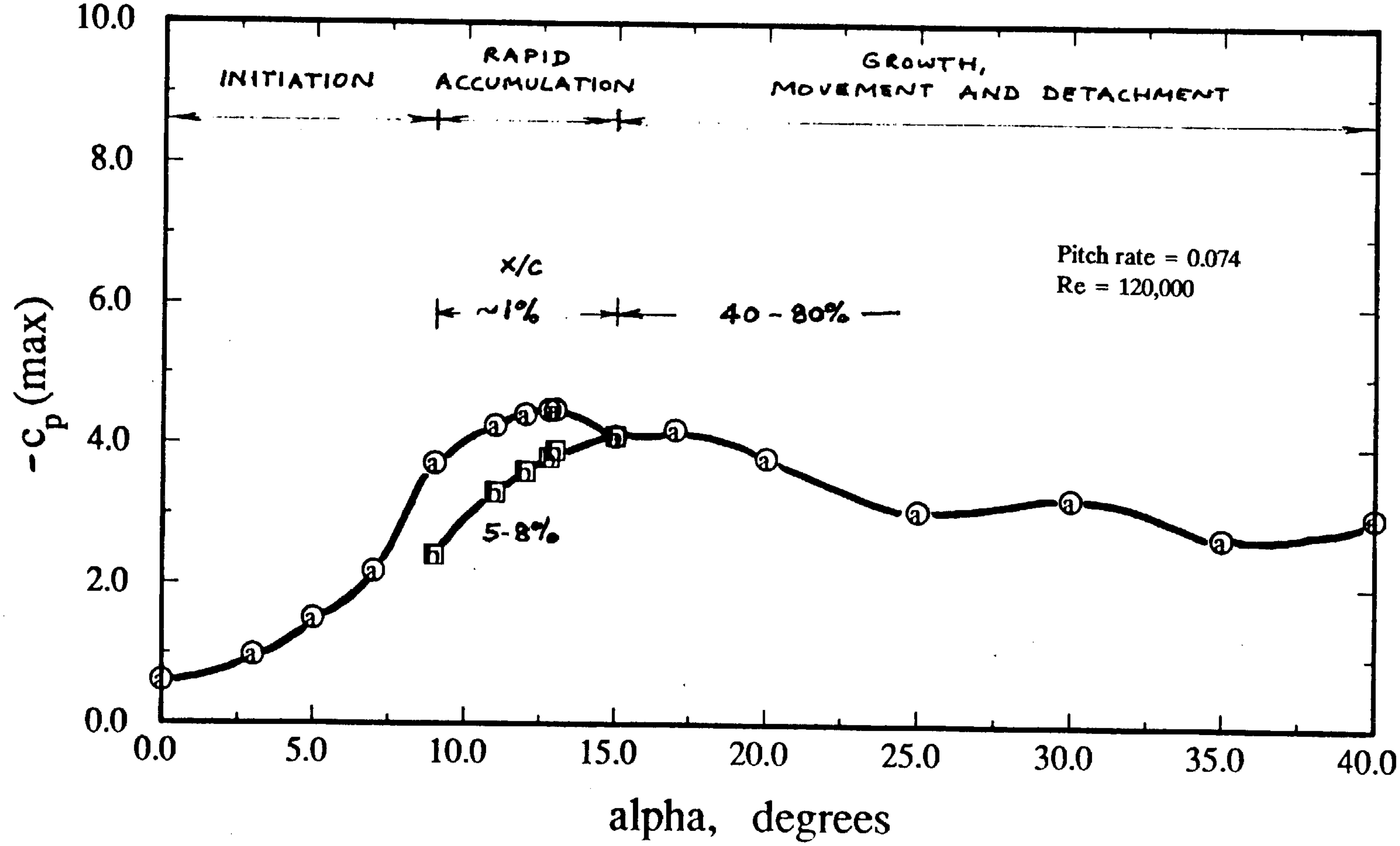

wall vorticity flux
114
64
14
-36
-86
-136
-186
-236
-286
angle, deg
5
10
15
20
25
30
35
40
x/c
0.0
0.2
0.4
0.6
0.8
Pitch rate = 0.074

Figure 5(a)



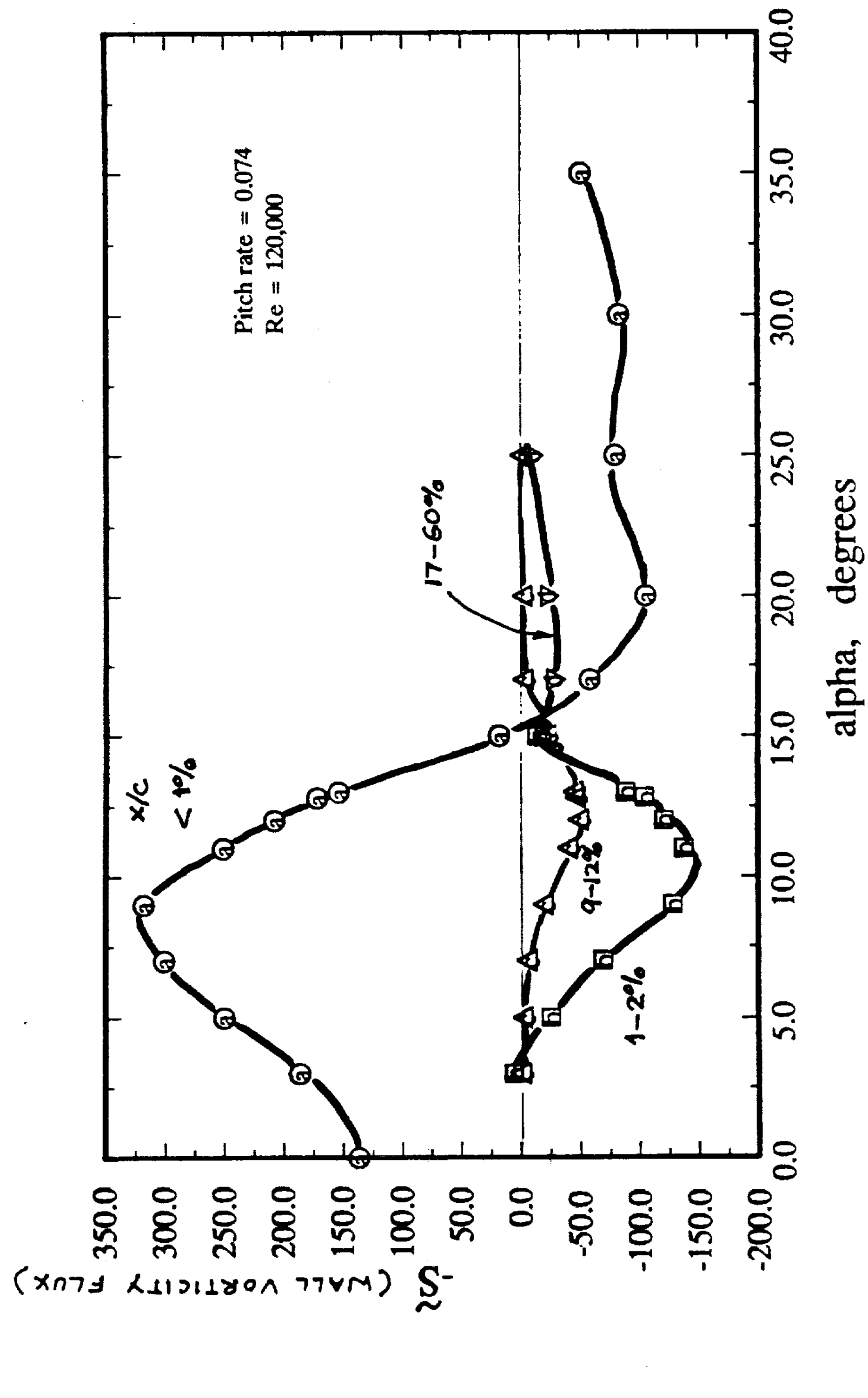
wall vorticity flux
189
139
89
39
-11
-61
-111
-161
-211
5
10
15
20
25
30
35
40
angle, deg
0.0
0.2
0.4
0.6
0.8
x/c
Pitch rate = 0.49 Re = 88000

Figure 5(b)



INITIATION
RAPID ACCUMULATION
GROWTH, MOVEMENT AND DETACHMENT
x/c
~1%
40 - 80%
5-8%
Pitch rate = 0.074
Re = 120,000
10.0
8.0
6.0
4.0
2.0
0.0
-c_p (max)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
alpha, degrees

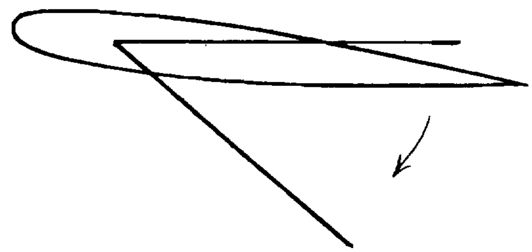
Figure 6(a)



Pitch rate = 0.074
Re = 120,000
x/c
< 1%
1-2%
9-12%
17-60%
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
-50.0
-100.0
-150.0
-200.0
-Ω (WALL VORTICITY FLUX)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
alpha, degrees

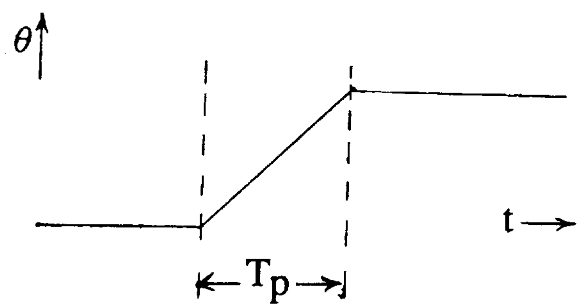
Figure 6(b)

EXPERIMENTAL ARRANGEMENT



NACA 0012 AIRFOIL, 0.3 m chord

PITCH-UP AT CONSTANT RATE; $0^{o} \leq \theta \leq 40^{o}$

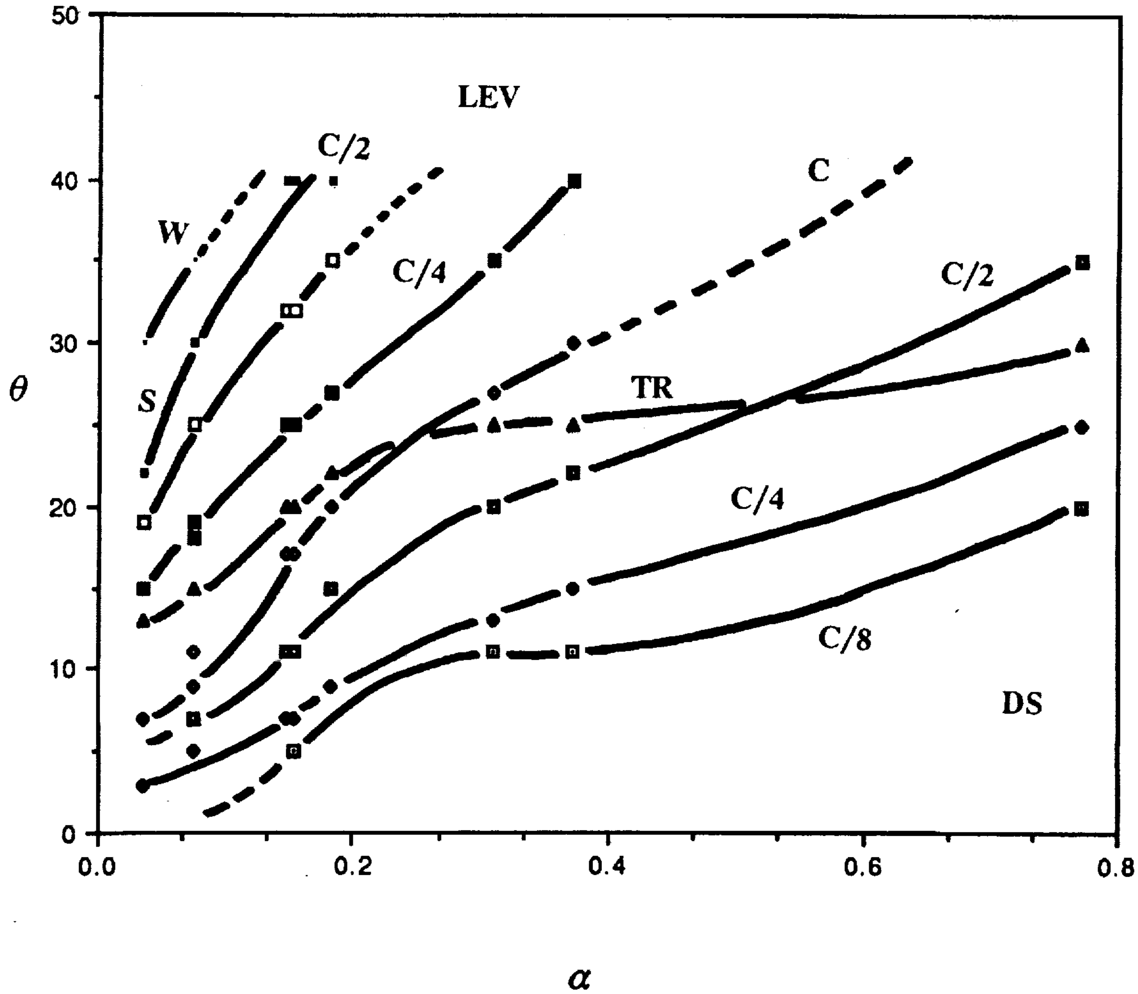


$2.8 \times 10^{4} \leq Re_{c} \leq 1.2 \times 10^{5}$ $\quad 0.036 \leq \alpha \leq 0.77$

$$\left[\alpha = \frac{\Delta\theta c}{T_p U_\infty}\right]$$

SEQUENTIAL EVENTS IN UNSTEADY SEPARATION PROCESS

(From flow-visualization records)



Generalization of Lighthill's discussion
of boundary layers shows that

The flux of vorticity from the wall
is proportional to the instantaneous pressure gradient

$$S = \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad S = S\frac{2c}{U_\infty^2}$$

- Combination of flow visualization, wall pressure and wall vorticity flux provide better understanding of the evolution of unsteady separation over a pitching airfoil

- The flux of vorticity at the wall is confined primarily to a region very close to the leading edge

- Trends in 'significant' events in wall pressure and vorticity flux have been mapped for a range of values of the dimensionless pitch rate

- Results point to alternatives for real-time identification of the state of flow development over the airfoil in unsteady situations